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Metal erosion under plasma flow typical for ITER transient regimes

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Abstract

Theoretical models of movement of a fast melt metal layer (up to v ~ 10 m/s) and droplet erosion are developed for power density pulses typical for tokamak plasma edge localized modes (ELM) and disruption. Fast melt metal movement and droplet erosion were shown to be possible only at plasma flow pressure P > 1 atm. The secondary shielding plasma near the target has a high density, a relatively low temperature and a much higher pressure than that of the original plasma flow. Even if initial plasma flow has a pressure below the threshold of fast melt layer movement and droplet erosion, the secondary shielding plasma can cause fast melt metal movement and droplet erosion.

Keywords: tokamak plasma disruption; melt metal layer movement; droplet erosion.

Plasma facing components are most intensively affected by plasma and heat load at transient processes such as ELM events and plasma disruption. Heat load on ITER divertor plates at ELM event is expected to be $Q = 0.2$—5 MJ/m^2 for τ = 0.1—1 ms, and at plasma disruption to be Q = 10—100 MJ/m^2 for τ = 1—10 ms [ITER Physics Basis (1999), Federici et al. (2001)]. Material cracking and brittle destruction studied in [Budaev et al. (2015)] are the most dangerous kinds of material degradation. Melt metal layer transfer from one place to another is danger because of tinning the plasma facing components. This process results in a more intensive erosion, an order of

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magnitude higher than the droplet erosion, whereas the droplet erosion is the main process of material carry over. According to [Poznyak et al. (2012)], fast movement (velocity up to ~10 m/s) of melt layer occurs when the temperature of the metal is a little higher than the material melting point. This can be explained [Zhytlukhin (2012)] by hydrodynamic processes. At the same time, the possible action of the plasma pressure gradient on melt metal is not sufficient for such melt metal movement. Electrodynamics force considered in [Bazylev (2012)] is also too low to explain the effect. The mentioned effects were observed on plasma accelerators in TRINITI, but up to now they have not been detected in tokamaks [Bazylev (2012)]. Motion of melt tungsten observed in Textor [Bazylev (2012)] has a much lower velocity v ≈ 1 cm/s. The work [Poznyak et al. (2012)] has shown that the initial hydrogen plasma flow strikes the target and spreads from the center to periphery of the target scraping off the part of melt layer from center to periphery. The material was displaced by several cm for ~1 ms. This means that the movement velocity is v ~ 10^3 cm/s.

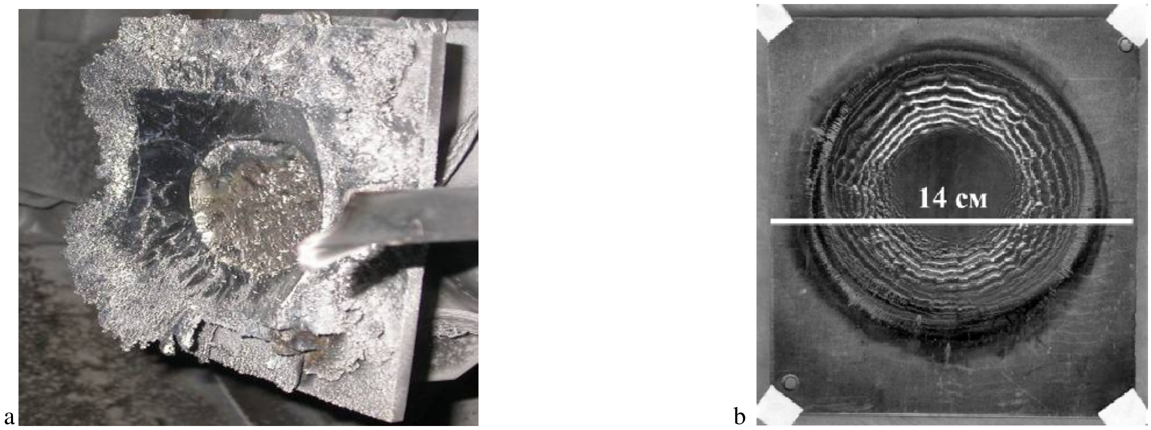

Fig. 1. (a) Beryllium plate (5 mm thick) after 70 pulses QSPA in the regime of Ar irradiation Qrad = 0.5 MJ/m2, 0.5 ms [Safronov] ; (b) – Niobium surface after series of QSPA pulses [Poznyak et al. (2012)].

On the melt surface waves arise due to Kelvin—Helmholtz instability at plasma flow directed radially from center to periphery over the surface. This suggestion was made already in the first work [Bakhtin et al. (1988)] where the waves created by plasma flow over melt metal were observed.

In this case, wave length (λ), frequency (ω) and increment (γ) are the following

$$\lambda = \frac{3\pi\alpha}{\rho' U^2}; \qquad \omega = \frac{2\pi U \rho'}{\lambda(\rho+\rho')}; \qquad \gamma = \frac{2\rho' U^3}{3\alpha}\sqrt{\frac{\rho'}{3\rho}}. \tag{1}$$

where α is the surface tension, ρ' and U are the density and the velocity of plasma flow, ρ is the metal density, $P = \rho' U^2/2$ is the pressure of plasma flow. We will show below that plasma flow over the metal surface is not only the initial plasma, but also the plasma of evaporated metal. The wave length decreases while ω and γ increase with the increase of plasma flow pressure. It is noticeable that $\omega \ll \gamma$ by $(3\rho/\rho')^{1/2} \approx 10^3$ times and there is no wave motion at a typical parameter of plasma flow $\omega \approx 10^3$ s^{-1} and pulse duration $\tau = 1$ ms. Instability is expressed as exponential growth of wave structure. However, growth of waves can be considered in linear approximation only up to height $H_0 = (\chi/\gamma)^{1/2} \sim 3\cdot10^{-4}$ см, (χ is the kinematic viscosity), when one can neglect the viscosity. At $H > H_0$ the wave behavior should be described by Navier-Stokes equation for viscous liquid flow. Plasma wind pressure deforms a wave profile. Wind pressure P is balanced by surface tension pressure at the lee side $P = \alpha/r$ ($r \approx (d^2y/dx^2)^{-1} \approx S^2/H$ is the curvature radius of wave). $P = \rho' U^2/2$ is the pressure of plasma flow moving parallel to the surface. Sole length of wave is $S = (\alpha H/P)^{1/2}$. Volume of the wave is constant because the development of Kelvin—Helmholtz instability and wave height growth decease when the plasma wind pressure and surface tension pressure are balanced. At $\lambda H_0 = SH$ we obtain

$$H = \frac{B}{\sqrt{PU}}; \qquad B = \frac{3^{7/4}\pi^{3/2}}{2^{2/3}}\sqrt{\alpha\chi}\left(\frac{\rho}{\rho'}\right)^{1/4}; \qquad S = \frac{B^{1/3}\alpha}{P^{5/6}U^{1/6}}. \tag{2}$$

For typical plasma flow (Q = 1.4 MJ/m^2, P = 2 atm, τ = 1 ms) on tungsten $S < \lambda$, and $H > H_0$. It means that the area H, where the plasma wind acts, increases after deformation and area S of wave contact with substrate decreases (the areas are related per a unit of wave crest length). Velocity of gliding wave crest can be determined from the equality of plasma pressure force (PH) and friction force $F = \rho\chi vS/H$. The velocity of the wave crest is

$$v = GP^{5/6}; \qquad G = \left(\frac{2}{\alpha\rho\chi}\right)\left(\frac{B}{U}\right)^{5/3}. \tag{3}$$

For plasma flow Q = 1.4 MJ/m^2, P = 2 atm, τ = 1 ms velocity of tungsten wave crest is v ~ 10 m/s. Wave crests for lighter metals move with a higher velocity ($v \sim 1/\rho$). Wave crests inertia is the reason why a crater radius is larger than the initial plasma flow radius and grows with plasma pressure increase [Poznyak et al. (2012)].

Maximum depth of a crater h created for a pulse can be estimated from crest volume SH, distance between wave crests λ and the number of waves leaving the crater n= $v\tau/\lambda$ during the pulse τ, the expression is $h = nSH/\lambda$. For tungsten, at the plasma flow Q = 1.4 MJ/m^2, P = 2 atm, τ = 1 ms, the crater depth is d ~20 μm.

The work [Bazylev et al. (2009)] shows that droplet emission from melt tungsten begins at a temperature a little higher than the melting point (Q = 1 MJ/m^2) when motion of melt layer begins. The observed droplet size is the same order of magnitude as the wave length. Droplets escape at angle <45° to the surface.

However, in earlier works [Guseva et al. (2002)] performed on plasma accelerator MKT (TRINITI) (Q = 0.3 MJ/m^2, τ = 60 μs, deuterium ion energy 1—2 keV, $P = 10^{-2}$ atm) droplet emission was also observed. But the droplet size $d \approx 1$ μm was 1.5 orders of magnitude lower than the wave length ~30 μm. The model [Martynenko et al. (2000)] explains small droplet emission by blowing away tops of wave crest by plasma wind.

Large droplets emission [Bazylev et al. (2009)] has another mechanism which is as follows. Kinetic energy of sliding crest $HS\rho v^2/2$ exceeds adhesion energy of crest with a substrate αS. But the crest can't be departed from the substrate without receiving a normal velocity component. If capillary waves arise on the crest of the main wave, the elevated part of the crest accelerates and catches up the foregoing wave. This part of crest can be separated from the surface as a droplet with size λ [Martynenko (2014)].

The effects described above – fast melt metal movement and droplet emission - can be realized only at plasma flow pressure P>~ 1 atm. Such pressure is typical for QSPA accelerators, whereas the expected plasma flow at ELM and disruption in ITER are P < 0.1 atm. On the basis of this comparison the authors of [Bazylev et al. (2009)] conclude that droplet erosion observed on QSPA will not take place in ITER in spite of the equality of power flow densities and pulses duration in QSPU and transient phenomena in ITER. However the primary plasma flow creates dense low temperature plasma of evaporated target material which has a much higher pressure than the primary plasma flow.

In the nineties a number of works [Hassanein and Konkashbaev (1995), Karlykhanov et al. (1996)] were performed on shielding plasma investigation. These works showed that density of shielding plasma can reach 10^{23} m^{-3} and temperature can reach several tens of eV. This shielding plasma is a good screen. It reduces energy deposited on the target one and more order of magnitude. However, the high pressure of shielding plasma flow over melt metal results in fast melt metal movement and droplet emission. We will point now some evidence of the role played by the shielding plasma in effects described above.

1. Plasma flow pressure in MKT accelerator [Guseva et al. (2002)] was lower than required for development of wave structure and droplet erosion. According to (1), at pressure of MKT plasma flow wave length of Kelvin—Helmholtz instability would be λ~1 cm (observed $\lambda \approx 30$ μm) and increment $\gamma << \tau^{-1}$.
2. Other evidence of shielding plasma influence on droplet emission is time dependence of droplets ejection obtained in [Bazylev et al. (2009)] (fig. 2). The escape of main droplets occurs after QSPA pulse completion.

Pulse duration is 0.5 ms whereas maximal droplet emission was observed at 1 ms and droplet emission lasted up to 2 ms. This means that droplet emission was initiated by shielding plasma which flows away slowly and regenerates itself by target and droplets evaporation caused by the shielding plasma.

3. The best evidence of shielding plasma action is simulation of disruption mitigation on QSPA. In this case, QSPA plasma flow acts on Ar gas target and Ar radiation acts on Stainless Steel. Radiation has zero pressure but the observed wave structure is a result of shielding plasma flow over the melt metal surface. In this regime dramatic erosion due to fast melt layer movement was shown on fig.1. In work [Martynenko (2014)] a wave structure was observed on stainless steel irradiated in QSPA in regime of Ar irradiation.

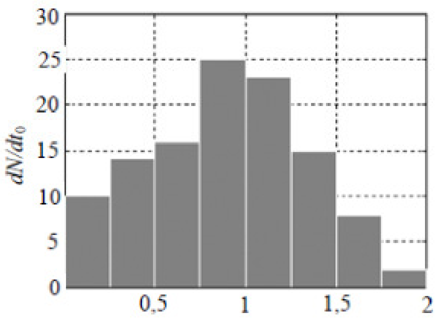

Fig. 2. Droplet emission vs. time. Pulse duration is 0.5 ms.

Wave structure development is understandable if we take into account that the initial plasma flow creates a secondary plasma with high density, low temperature and high pressure. Flow of high pressure secondary plasma is the reason for wave structure formation and droplet erosion.

The main factor determining the shielding plasma formation is power density which determines an evaporation rate. But it should be noted that droplets evaporation increases the shielding plasma density. Shielding plasma creation can start with evaporation of surface contaminations, mobilized dust particles and other deposits. After the droplet emission has started, existence of shielding plasma will be supported by evaporation of droplets.

One should emphasize that use of parameter of initial plasma flow to estimate the melt metal layer motion and droplet erosion is not correct. For quantitative calculations of melt layer movement and droplet erosion one need study of shielding plasma characteristics in dependence of initial plasma flow.

Thus, the shielding plasma reduces the energy flow reaching the surface. At the same time, the shielding plasma is a reason of the most dangerous metal erosion – fast movement of the melt layer and droplets emission.

References

Bakhtin, V.P., Vasilev, V.I., Grebenstchikov, Yu.B., Konkashbaev, I.K., Kucheryavyi, Yu.V., Myanko, V.I., Strunnikov, V.M., 1988. Wave generation on melt metal surface by plasma flow, 1st All Union Conf. «Constructive Materials Properties Modification by Beams of Charged Particles». Part I, pp. 108—110.

Bazylev, B., 2012. Modeling of W melting experiments and extrapolation for ITER, 17th ITPA Meeting on Divertor—SOL Physics, 15—17 October.

Bazylev, B., Janeschitz, G., Landman, I., Laorte, F., Klimov, N.S., Podkovyrov, V.L., Safronov, V.M., 2009. Experimental and theoretical investigation of droplet emission from tungsten melt layer. Fusion Engineering and Design 84, 441-445.

Budaev V.P. Martynenko, Yu.V., Karpov, A.V., Belova, N.E., Zhitlukhin, A.M., Klimov, N.S., Podkovyrov, V.L., Barsuk, V.A., Putrik, A.B., Yaroshevskay, A.D., Giniyatulin, R.N., Safronov, V.M., Khimchenko, L.N., 2015. Tungsten recrystallization and cracking under ITER-relevant heat loads. Journal of Nuclear Materials 463, 237–240.

Federici, G., Skinner, C.H., Brooks, J.N., Coad, J.P., Grisolia, C., Haasz, A.A., Hassanein, A., Philipps, V., Pitcher, C.S., Roth, J., Wamplerk, W.R., Whyte, D.G., 2001. Plasma-material interactions in current tokamaks and their implications for next step fusion reactors. Nuclear Fusion 41, 1967.

Guseva, M.I., Gureev, V.M., Domantovskii, A.G., Martynenko, Yu.V., Moskovkin, P.G., Stolyarova, V.G., Strunnikov, V.M., Plyashkevich, V., Vasilev, V.I., 2002. Tungsten surface erosion and erosion product morphology in experiments simulating plasma disruption. Journal of Technical Physics 72(7), 40-51.

Hassanein, A., Konkashbaev, I., 1995. Comprehensive model for disruption erosion in a reactor environment. Jorunal of Nuclear Materials 220-222, 244-248.

ITER Physics Basis, 1999. Nuclear Fusion 39, 2137.

Karlykhanov, N.G., Martynenko, Yu.V., Matveeko, Yu.I., Moskovkin, P.G., Politov, V.Yu., 1996. Interaction of a plasma flow with a solid target. Plasma Physics Reports 22(11), 903-911.

Martynenko, Yu.V., 2012. Metal surface erosion as result of wave relief formation under intensive plasma flow. Problems of Atomic Science and Technology. Ser. Thermonuclear Fusion 3, 41-43.

Martynenko, Yu.V., 2014. Movement of melt metal layer and droplet erosion under plasma flow action typical for ITER transient regimes. Problems of Atomic Science and Technology. Ser. Thermonuclear Fusion 37(2), 53-59.

Martynenko, Yu.V., Moskovkin, P.G., 2000. About droplet erosion at plasma disruption in tokamaks. Problems of Atomic Science and Technology. Ser. Thermonuclear Fusion 1, 65-69.

Poznyak, I.M., Klimov, N.S., Podkovyrov, V.L., Safronov, V.M., Zhytlukhin, A.M., Kovalenko, D.V., 2012. Erosion of metals under the action of intense plasma stream. Problems of Atomic Science and Technology. Ser. Thermonuclear Fusion 4, 23-33.

Safronov, V.M., Private communication.

Zhytlukhin, A.M., 2012. Workshop on ITER first wall and diverter, Zvenigorod, 14 February.